# Effect of Thermal Comfort on Occupant Productivity in Office Buildings: A Response Surface Analysis Approach

Dr Amit Kaushik, Prof Mohammed Arif, Dr Prasad Tumula, Prof John Obas Ebohon

## Abstract

Thermal environment is one of the main factors that influence occupants' comfort and their productivity in office buildings. There is ample research that outlines this relationship between thermal comfort and occupant productivity. However, there is a lack of literature that presents mathematical relationship between them. This paper presents a research experimental study that investigates effects of indoor environmental quality factors on thermal comfort and occupant productivity. This study was conducted by collecting indoor environmental quality parameters using sensors and online survey for twelve months. Data analysis was done using Response Surface Analysis to outline any mathematical relationship between indoor environmental quality and occupant productivity. The outlined relationships confirmed dependencies of occupant thermal comfort and productivity on various indoor environmental factors. These dependencies include the effect of $CO_2$ concentration, VOC concentration. These relationships were analysed to rank nine indoor environmental parameters as per the degree of effect on occupant thermal comfort and productivity. These findings would help design professionals to design better office design that would improve occupants' comfort and their productivity. Study results have different implications for professionals working in design, construction and operation of office buildings. It is recommended that design guidelines for office buildings should consider occupant productivity and incorporate recommended range for indoor environmental quality parameters in respective categories and criteria.

## 1 Introduction

Majority of the adults spend up to 90% of their time indoors. It is profoundly affected by their geographical location, job requirement, season and age (ASHRAE, 1993, Indraganti et al., 2015, Al-Esia and Skok, 2015). For instance, Adult spend up to 90%, and children spend 75% indoors (Bernstein et al., 2008, Brasche and Bischof, 2005). It is primarily due to the job requirement of adults. Mass industrialisation and urbanisation in the past fifty years have led to a significant shift from a factory or outdoor working environment to an indoor working environment in office buildings. An efficient and conducive working environment is a vital and fundamental requirement for occupants to work efficiently (Lan et al., 2011b). Indoor environmental quality has significant effect on occupants' comfort and their productivity in offices (Collinge et al., 2014, Council, 2014, World Green Building Council, 2014, De Been and Beijer, 2014, Leaman and Bordass, 1999, Oseland and Bartlett, 1999). Occupant productivity in office buildings has significant impact on organisation's financial performance and overall growth. Organisations in developed economies have reported having employee salary expenditure many times higher than operational cost of the building (Woods, 1989, Kats, 2003). Improving the indoor environment and its quality could result in substantial amount of improvement in occupant productivity and organisation's profit (Fisk et al., 2012, Seppänen and Fisk, 2006). A study conducted in the UK suggests that a pleasant indoor environment can help save up to £135 billion per year (Wheeler and Almeida, 2006). There are several studies that indicate the cause and effect relationship between productivity and indoor environment. However, there is a lack of studies outlining mathematical relationships between them and any interdependencies between the physical factors of indoor environment. The physical indoor environment is comprised of different types of factors such as thermal comfort, indoor air quality, lighting quality (visual comfort), acoustic comfort, and Office layout.

Amongst all the factors, thermal comfort has the highest influence on occupants' comfort and their productivity (Alajmi et al., 2015, Langevin et al., 2013, Frontczak and Wargocki, 2011). This research paper focuses on thermal comfort and its impact on occupant productivity in office building.

# 2 Thermal Comfort

Thermal comfort literature can be traced back to the early twentieth century (Dufton, 1929, Dufton, 1930). Early works highlight the initial steps towards understanding the effect of temperature of an indoor environment on human comfort and work (Winslow and Gagge, 1941, Gagge et al., 1941, McGill, 2015). (ASHRAE, 2004) defines comfort as the mental state of satisfaction with the thermal environment. It is a highly subjective state dependent on numerous physical, physiological and psychological factors (Lin and Deng, 2008), due to its dependence on highly independent and various categorical factors. These factors range from clothing, physical activity and seating, to location, posture and mental state (mood) (ASHRAE, 2005). Human factors that influence thermal comfort are age, gender, metabolism, local climate and geography (Quang et al., 2014, Cena and de Dear, 2001). Thermal comfort is the cumulative response of occupants towards the thermal state, created by different physical parameters. Attaining thermal comfort for all the occupants in a building becomes a complicated attempt.

Human response to thermal comfort is broadly described using three concepts; thermal sensation, thermal preference and thermal acceptability (Langevin et al., 2013). Thermal comfort and sensation are akin but differ in nature, i.e. thermal comfort is subjective, but the sensation is objective (Hensen, 1991). ASHRAE defines thermal sensation as an occupant's sensory perception of the immediate environment (ASHRAE, 2010). The literature outlines six primary factors that influence the thermal comfort of an occupant. These are air temperature, relative humidity, mean ambient temperature, clothing insulation and metabolic rate (Macpherson, 1973, Goldman, 1999, Berglund, 1977, Macpherson, 1962, Djongyang et al., 2010). Thermal preference of an occupant is the ideal thermal condition in an environment, whereas thermal acceptability is an occupant's level of approval of the thermal environment (Langevin et al., 2015, Langevin et al., 2013).

Regarding the measurement of thermal comfort, Fanger proposed a thermal comfort predictive model. It works on four physical parameters and two individual variables to define PMV (Predicted Mean Vote) (Lin and Deng, 2008, Fanger, 1984, Fanger, 1970). These are:

1. Air temperature
2. Air velocity
3. Mean radiant temperature
4. Relative humidity
5. Clothing insulation
6. Activity level

PMV helps to calculate a predicted percentage of dissatisfied occupants (PPD). PPD is used to predict the likely percentage of people who would feel on the scale of +3 (hot), +2 (warm), +1 (slightly warm), 0 (neutral), -1 (slightly cool), 2 (cool), -3 (cold) (Olesen and Parsons, 2002). It is based on heat balance theory and thermoregulation physiology (Charles, 2003). One of the drawbacks of this method is that it needs a climatic chamber so that data can be collected in it. It limits its application in some real-world scenarios.

De Dear (1998) proposed another thermal comfort approach; it is based on the occupant's acceptability of the thermal environment. It outlines that the occupant's thermal acceptability of an environment affects occupant thermal comfort. It is highly dependent on human adaptation behaviour based on a physiological and psychological adaptation of the individual (de Dear and Brager, 1998, Brager and de Dear, 1998). This approach has been widely used in temperate climate conditions.

There are different thermal comfort standards developed across the globe, based on the above research (ASHRAE, 2005, ASHRAE, 2004, ASHRAE Standard, 1992, De Dear and Brager, 2002). These standards have been developed on the model and studies based in

North America and Northern Europe (Ogbonna and Harris, 2008). Also, they are applicable for uniform and static thermal conditions and do not count in various human-specific factors like age, local climatic conditions, gender, metabolic rates and thermal preferences and expectations (Han et al., 2007). Due to these limitations, there are hesitations and reluctance towards the global acknowledgement of discussing standards in the context of varied climatic conditions and a range of indoor actions in an office environment.

Thermal comfort has a strong influence on occupant productivity. Occupants that report complaints of thermal discomfort have reported low productivity (Roelofsen, 2015, Lan et al., 2011a, Akimoto et al., 2010, Tarantini et al., 2017, Lipczynska et al., 2018). Research indicates that temperature is crucial for occupant productivity. An office environment has a range of purposes, such as reading, typing and learning activities. Temperature from 18°C to 30°C has observed a diverse response to occupant productivity. In an office environment, 21°C - 25°C is observed to be the optimum temperature range for comfort. If the temperature goes above 25°C, every 1°C reports a 2% drop in productivity till 30°C (Kekäläinen et al., 2010, Seppänen and Fisk, 2006, Seppanen et al., 2003). Research evidence also suggests that productivity may not lie in the centre of the comfort range. The optimum temperature for productivity for different office tasks vary within the thermal comfort range (Tanabe et al., 2007). For instance, creative tasks may have a comfortable temperature range (21°C - 25°C), but intensity and speed required in/for an office work may need marginally cold temperature for optimal productivity (Fisk, 2000a, Fisk, 2000b). It outlines that within the thermal comfort range, there are different micro range required to achieve maximum productivity. It emphasises the gap in the current practice of various design guidelines with a wide range of indoor parameters for occupant health. While an occupants' comfort range is maintained, it is not necessary that occupants would be productive throughout the range of that temperature. There is a need to identify the productivity range within the comfort range of thermal comfort. Current building design guidelines don't directly aim towards providing comfortable range and that doesn't always cater to productivity (Al Horr et al., 2016b). Hence, there is a gap in addressing productivity in office design (Al Horr et al., 2016a). Also, there is literature that supports that thermal comfort parameters influence occupant productivity (Council, 2014). However, there is lack of research on its range and mathematical relationship between occupant productivity and thermal comfort parameters. This research would aim to establish relationship between these parameters (temperature, relative humidity) and occupant productivity (Kaushik, 2019). It also aims to identify any indirect effect of other indoor environment parameters such as air quality, light, sound and office layout on thermal comfort of the occupants.

It led to design an experiment that can establish the above-mentioned relationships. The next section describes the experiment design for this research.

## 2.1 Experiment Design

The primary drivers of designing the thermal environment of a building should be based on its contextual climate conditions, the building's layout and orientation, material and occupant behaviour. Field studies reviewed recommend that Post Occupancy Evaluation (P.O.E) is an effective way to measure the effect of indoor environmental quality factors' on occupants' comfort and their productivity (Silva et al., 2017, Göçer et al., 2015, Collinge et al., 2014, Hua et al., 2014, Hirning et al., 2013, Gou and Lau, 2013). Amongst six thermal comfort factors, temperature (ambient) and relative humidity have the greatest influence on thermal comfort (ASHRAE, 2004, Djongyang et al., 2010). This research study used P.O.E to collect occupant response and deployed sensors for physical measurement of temperature and relative humidity. The experiment was conducted in an office located in Doha, Qatar. Qatar has a subtropical desert climate. It faces arid, hot and humid summer with low annual rainfall. Harsh local weather forces habitants to spend most of their time indoors. It has also led to the development of significantly insulated buildings to control the indoor environment and provide comfort and wellbeing to the occupants. It acts as an opportunity to investigate this topic in Qatar. People spending most time indoors with a controlled indoor environment meant that office acts as a more effective working laboratory for the experiment. A medium-sized office with 40 employees was used for the experiment. It was divided into 12 zones and sensors were installed accordingly (Appendix -1). The data was analysed using Response Surface Methodology in MiniTab. The outcomes were regression equation that determines the mathematical relationship between independent (indoor parameters) and dependent (occupant productivity) variables. It also produced R-square value that determines the degree of relationship between independent and dependent variables and contour and surface plots that present the multinomial relationship between occupant productivity and various indoor environmental parameters.

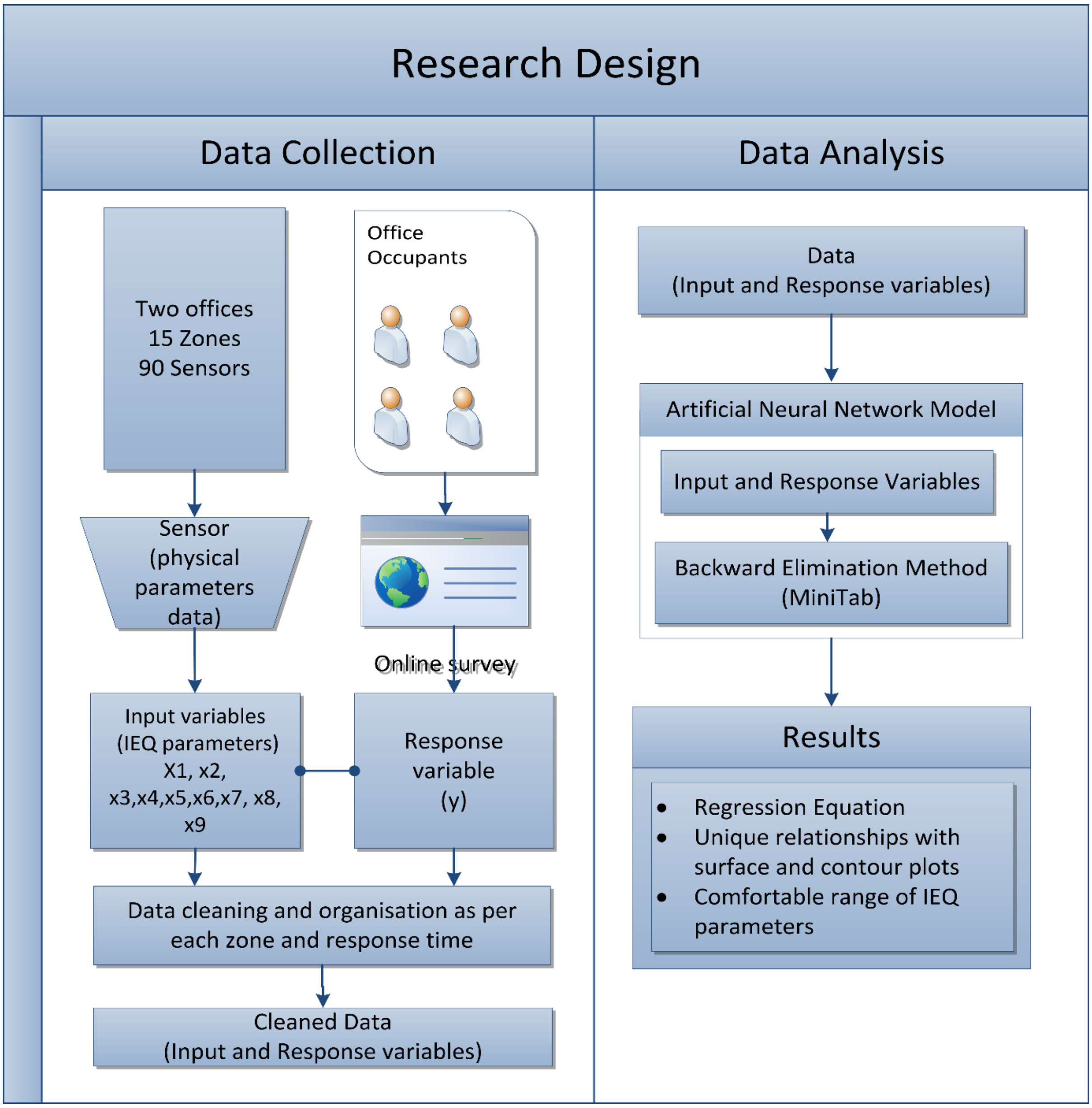


**Figure 1 - Research Design**

## 2.2 Occupant Survey

The study involved sending an online survey to occupants every fortnight by the Human Resource department of the organisation. The data was collected and stored safely, and employee profiles were managed using data encryption and were kept anonymous. The replies were time-stamped along with their zone. Research team created a questionnaire (Table – 1) for occupants to fill online. This survey instrument was developed after analysing multiple subjective assessment, survey instruments currently being used for Post Occupant Evaluation (Dykes and Baird, 2013, Bordass et al., 2001, Bluyssen et al., 2011, Stokols and Scharf, 1990, (AMA), 2004). It was designed to focus on six indoor environmental quality factors. Other indoor environmental quality factors were collected and included in the analysis to outline any implicit effect of non-thermal factors on thermal comfort and productivity using Response Surface Methodology. The main experiment also focused on other indoor environmental quality factors and collected physical data and occupant response. However, this paper only presents the results from the analysis conducted for the thermal comfort questions. Literature outlined that thermal comfort has two parameters (temperature, relative humidity) with maximum influence on occupants' comfort and their productivity. Other questions are included in the analysis to highlight any interdependencies or relationships. Response Surface Analysis enables to underline and present any inter-dependencies (as presented in the result).

The survey asked occupants to respond to temperature and relative humidity on how they were affecting their productivity. The response ranged from very negative to very positive based on Likert scale (Allen and Seaman, 2007). Survey responses were devised to provide more options for occupants to describe their situation. In this study, "Positive" response means that occupant feels that particular indoor environmental parameter has a positive effect and occupants feel they are slightly more productive than normal. In the case of "very positive", the occupant feels highly productive as compared to the normal scenario.

Each response was time-stamped along with the zone to ensure that temperature and relative humidity measurement were accurately calculated (average of past hour). The survey response was collected online on fortnightly and time stamped. Hence, they can be correlated with the sensor data for each data point. In the response surface methodology term, these data points can also be termed as *runs*. The runs would enable us to calculate and generate several relationship equations between seven input variables and the performance variable(y).

Question - How have these factors affected your productivity?

| | Indoor environment factor | Very Negatively | Negatively | Neutral | Positively | Very Positively |
|---|---|---|---|---|---|---|
| A | Thermal comfort | | | | | |
| B | Natural ventilation | | | | | |
| c | Mechanical ventilation | | | | | |
| D | Low-emitting materials | | | | | |
| E | Illumination levels | | | | | |
| F | Daylight | | | | | |
| G | Indoor chemical & pollutant source control | | | | | |
| H | Acoustic quality | | | | | |

| | | | | | | |
|---|---|---|---|---|---|---|
| I | Office layout | | | | | |

Table 1 - Survey Questions

### 2.3 Physical Parameters Measurement

The physical environment data was collected using ambient temperature and relative humidity sensors in each zone. The experiment used factory sensors for all the environmental parameters. Literature also outlined that outdoor temperature and relative humidity has an indirect impact on occupants' comfort and their productivity inside mechanically ventilated buildings (Humphreys, 2005, Humphreys and Nicol, 2000). Hence outdoor temperature and relative humidity sensor was also installed to map any effect of outdoor thermal environment on occupants' comfort and their productivity. All the sensors were connected to a base unit (BRE base unit) which uploaded the data to online repository that allowed downloading the data in excel file (Table -2). Temperature was measured in °C, Relative Humidity in percentage, Carbon Dioxide in concentration levels of Particles Per Millions (PPM). Illuminance were measured in lx levels. Noise was measured in decibels (dB) and Volatile Organic Compound (VOC) concentration was measured TVOC (Total Volatile Organic Compound) free air in percentage. The sensor used provided readings as percentage of TVOC in air. All sensors were factory calibrated and installed by supplier's technician. Sensors were monitored by two on-site technicians to ensure that they were working efficiently. All the sensors worked between with 1 – 5% tolerance and reported readings per minute. These readings were then averaged 15 minutes and then hourly based on the time stamp of the survey. Both survey and sensor data were organised based on each zone.

| IEQ factor | Parameter | Measured by | Input Variable | Response/ performance variable |
|---|---|---|---|---|
| Thermal comfort | Temperature (Mean Ambient) | Zigbee T-3524C | $x_1$ | $y$ (calculated from the survey responses) |
| | Relative humidity | | $x_2$ | |
| | Outside Temperature (Mean Ambient) | Vantage Pro | $x_3$ | |
| | Outside R.H | | $x_4$ | |
| Indoor Air Quality | Carbon dioxide | Zigbee T-3571 | $x_5$ | |
| | Total Volatile Organic Compound | Zigbee T-3576 | $x_6$ | |
| Lighting | Illuminance level (lx) | | $x_7$ | |
| Noise | Sound level (Decibel - dB) | Zigbee T-3551 | $x_8$ | |

| | | | | |
|---|---|---|---|---|
| Office Layout | Seating Arrangement | Researcher (Office plan) | $x_9$ | |

**Table 2 - IEQ Parameters Measurement**

# 3 Data Analysis: Response Surface Methodology

This research study used Response Surface Methodology (RSM) for data analysis. It provides a framework for analysing the IEQ parameter data and occupant survey data to develop various statistical relationship models that outline the degree of influence of each IEQ factor on occupant productivity. RSM is a collection of statistical and mathematical techniques used to develop and interpret polynomial equations (Box and Draper, 1987, Montgomery and Myers, 1995). The main aim of the RSM model is to investigate independent variables, test empirical models for developing an appropriate relationship between the response and the input variables and to optimise methods for estimating values of $x_1$, $x_2$,….,$x_k$ that produce the most desirable value of y(Ximénez and San Martín, 2000, Box and Draper, 1987, Hill and Hunter, 1966).

*f* = $y = f(x_1, x_2, \dots\dots, x_k) + \varepsilon$

$y$ = *response/ performance variable*

$x$ = *input variables*

$\varepsilon$ = *noise or error observed in the response* $y$

The surface represented by $f(x_2, \dots\dots, x_k)$ is called the response surface. It can be represented graphically (three-dimensional space or as contour plots) that helps to understand the shape of the response surface.

Indoor environment is a complex state and it has several parameters that are interconnected and influences the overall environment and occupants' health and comfort. Response Surface analysis is an efficient approach to establish relationship between input variables and their effect on output variable. This method helped the study to outline any implicit relationship between the input variables (indoor environment parameters) and their effect on output variable (thermal comfort and productivity). It used RSM to generate the relationship between nine parameters (under five indoor environmental factors) and occupant response (Survey).

The data was collected for twelve months and resulted in 500 survey data points. After the cleaning and adjustment, 368 data points were used to perform the analysis. The data was collected using online survey. It was designed to start with default start point of all questions at neutral and participants could choose to change and select different comfort options. Any survey weblink disconnected without using submit option was treated as incomplete whether surveys with half completed or left without changing any options. The response surface analysis was conducted using Minitab software. The researcher used a backward elimination procedure to conduct response surface analysis. This process is highly useful to eliminate any input variable with low effect on output variable in any multiple regression analysis. Backward elimination starts with all the input variables in the model and eliminates one input variables in each run with the least effect on the model. This stepwise procedure continues until the no input variables in the model have a p-value greater than the value specified (alpha to remove). The researchers used 0.1 as alpha to remove the value in this experiment. It produces results with 90% confidence.

# 4 Results

The data analysis was conducted using nine environmental parameters against set of questions. The results presented in this section are divided in three parts; ANOVA, regression analysis and response surface analysis.

## 4.1 Analysis of Variance (ANOVA)

Analysis of Variance analysis was used to highlight the effect of thermal comfort on occupant productivity. It was done using a = 0.1 (90% accuracy). The experiment was based identify independent factors that affect occupant productivity. Results indicated that temperature, relative humidity have highest impact (p value <0.005) and outside temperature and outside humidity with high impact (p value < 0.012) on occupant productivity. It also indicated that square of temperature and humidity were found have significant impact on productivity. Interestingly, the two-way interaction of any thermal parameter with non-thermal parameter such as sound, kind of workspace and light also indicated to have strong impact on occupant productivity.

## 4.2 Regression Analysis

As part of Response Surface Analysis, Regression analysis was also conducted. This study presents $R^2$ (statistical test) value that indicates a strong relationship between independent and dependent variables. It produced adjusted R-square (coefficient of determination) value to be 73.79%. It indicates that 74% of the data fits the regression. It highlights that there is a significant relationship between dependent and independent factors. It also produced regression equation (presents only up to three decimal places).

| | | | | |
|---|---|---|---|---|
| Occupant Productivity | = | -52.08 | + 5.666 T | - 0.1318 R H |
| | | - 0.015 O T | | - 0.0836 O R H |
| | | + 0.00637 CO2 | | - 0.0468 VOC |
| | | - 0.11728 T*T | | |

- Temperature – T
- Outside Temperature – O.T
- Relative Humidity – R.H
- Outside Relative Humidity – O.R.H

Regression equation explains the effect of the independent variable (temperature, relative humidity, outside temperature, outside relative humidity etc.) on the dependent variable (thermal comfort). The equation includes input variables with a p-value higher than 0.01. These variables include sound and type of workspace. Removing these variables led to a decrease in R-value of the equation. While these variables contribute to the overall equation, they do not have any direct impact on the output variable. In the above equation, - 52.08 is the intercept (constant). Regression equation shows that thermal comfort depends on the temperature. When temperature increases by 1°C, thermal comfort increase in 5.666 units. Similarly, when relative humidity increases by 1%, thermal comfort decreases by 0.1318 unit. There are also quadratic dependencies such as a 0.11728 T*T. Hence, when the temperature increases by one unit, the thermal comfort increases to 5.666 units, minus a 0.11728 Temperature*Temperature.

As part of the analysis, Collinearity amongst the independent variables was investigated to identify any unreliability of the relationship and estimates of any regression analysis. Multicollinearity refers to any linear relationship that leads to any skewness or error in result (Mansfield and Helms, 1982, Gunst and Webster, 1975). There are multiple ways to identify multi-collinearity in a regression. However, VIF (Variance Inflation Factor) is the most reliable indicator of any correlation between the independent variables. Literature indicates that VIF value up to 5 doesn't indicate high correlation and doesn't require any measure to remove collinearity. VIF values up to 10 indicate high correlation but their impact is subjective in nature and depend on $R^2$ and individual P -value. (Daoud, 2017, Paul, 2006). In this regression analysis, Majority of the independent variables have VIF values lower than five. Variables such as sound, office layout and illuminance have higher VIF. However, their p-value is also higher than 0.05 indicating that they have minimal influence on the dependent variable (thermal comfort and productivity).

## 4.3 Response Surface Analysis

Contour and surface plots are used to show the effect of two independent variables (predictor variables) on the response variable (dependent). They are used to identify optimal results. They are used to show the variation of response in detail to outline the optimum response and show the overall profile of the response as per the variations of independent variables (Myers et al., 2016). This study provides several unique relationships between two indoor environment parameters and thermal comfort. Each relationship describes unique effects and range of independent variables on dependent variables. They also highlight any interdependencies of independent variables. The main contribution of this study is to outline the various implicit effects of different indoor environmental factors on thermal comfort and productivity. The analysis of each result has resulted in a ranking system presented in the discussion section. The following relationships were the outcome of the response surface analysis (Table – 3).

| S.no. | Independent variable 1 | Effect & Range | Independent Variable 2 | Effect & Range | Inference |
|---|---|---|---|---|---|
| 1 | Volatile Organic Compound | 85% VOC free air | Outside Relative Humidity | None | VOC has a direct effect on thermal comfort and productivity |
| 2 | Carbon Dioxide | Positive effect up to 700 PPM | Outside Relative Humidity | None | Carbon dioxide has effect on thermal comfort and productivity |
| 3 | Carbon Dioxide | Positive effect up to 700 PPM | Outside Temperature | 22- 45°C | Both carbon dioxide and outside temperature influences thermal comfort and productivity. |
| 4 | Carbon Dioxide | None | Relative Humidity | Positive up to 60% | R.H has direct influence on thermal comfort and productivity as compared to carbon dioxide |
| 5 | Outside Relative Humidity | No direct impact | Relative Humidity | Positive up to 55% | Outside R.H doesn't have a direct impact on thermal comfort. However, it influences the impact of indoor |

| | | | | | |
|---|---|---|---|---|---|
| | | | | | R.H on comfort and productivity. |
| 6 | Temperature | Positive 21-25°C Very Positive 22-24.5°C | VOC | Positive VOC Free air – 65% 7 & above Very Positive - Above 90% | Temperature has stronger influence as compared to VOC. |
| 7 | Temperature | 22-24°C | Carbon Dioxide | Up to below 650 ppm. | Temperature has stronger influence as compared to carbon dioxide. |
| 8 | Temperature | 21-24°C | Outside Temperature | 30-40°c | Both outside and inside temperature have strong impact on occupant's thermal comfort and productivity |

**Table 3 - Results Table**

### 4.3.1 Effect of VOC, Outside Relative Humidity on Thermal Comfort and its impact on Occupant Productivity

This relationship represents the effect of VOC and the outside relative humidity on occupant thermal comfort and productivity. Plots are measured at typical hold values of various independent variables. As per the existing literature, the overall comfort level goes down as the VOC level increases (Panagiotaras et al., 2013). This analysis also indicates a positive relationship between occupant thermal comfort, productivity and VOC free air (VOC free air by percentage). It suggests that when VOC free air is above 85%, it has a positive effect on thermal comfort and productivity. However, outside relative humidity doesn't have much effect along when compared to VOC.

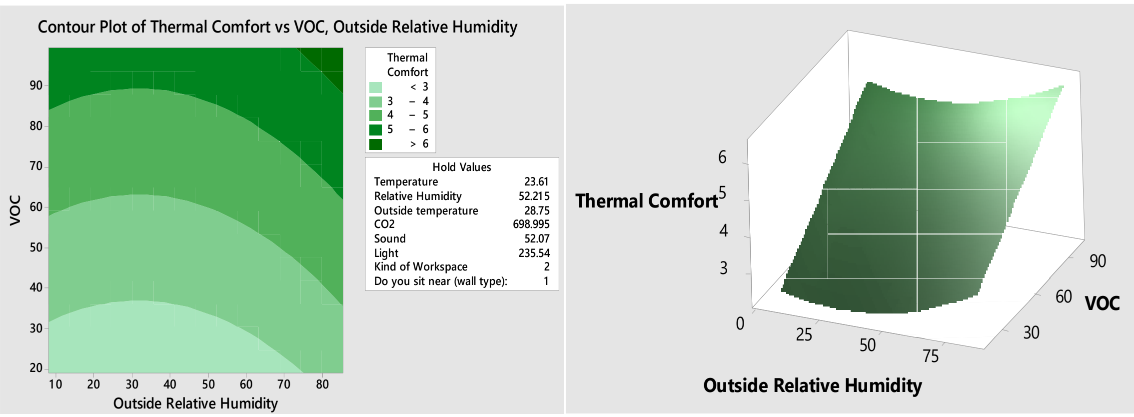


**Figure 2 - Surface & Contour Plot - Effect of VOC & ORH on Thermal Comfort and Occupant Productivity**

Each relationship produced above contour and surface plots (Figure – 3). However, due to the length restriction of the paper, the rest of the graphs are available on request.

#### 4.3.2 Effect of Carbon Dioxide and Outside Relative Humidity on Thermal Comfort and its impact on Occupant Productivity

This relationship highlights the effect of carbon dioxide and outside relative humidity on occupant thermal comfort and its impact on productivity. The plots indicate that carbon dioxide has a more prominent effect on productivity than outside relative humidity. Optimum productivity is observed around 400-700 ppm of $CO_2$ concentration.

#### 4.3.3 Effect of Carbon Dioxide and Outside Temperature on Thermal Comfort and Occupant Productivity

This relationship shows the effect of carbon dioxide and outside temperature on occupant productivity. It can be seen that the highest level of productivity is achieved at 30-40°C with $CO_2$ concentration below 400 ppm. Also, productivity is positive until 700 ppm of carbon dioxide and when outside temperature ranges from 22-45°C. It highlights that outside temperature has more effect on an occupant's thermal comfort and its impact on productivity as compared to carbon dioxide.

#### 4.3.4 Effect of Carbon Dioxide and Relative Humidity on Thermal Comfort and Occupant Productivity

This relationship presents the effect of carbon dioxide and relative humidity on thermal comfort and their impact on the occupant productivity. In this multinomial relationship, relative humidity has direct and stronger influence on thermal comfort and productivity as compared to carbon dioxide (Ismail et al., 2008, Tsutsumi et al., 2007). Relative humidity has a positive effect on an occupant's comfort levels up until 60%.

#### 4.3.5 Effect of Outside Relative Humidity and Relative Humidity (indoor) on Thermal Comfort and its impact on Occupant Productivity

This relationship outlines the effect of outside relative humidity and inside relative humidity on occupant thermal comfort and productivity. They outline that relative humidity (indoor) has a positive impact up until 55% but show no impact from 55%-70% on occupants' thermal comfort and productivity. These results vary slightly from the current expected humidity range (30-70%). Current comfort ranges are set based on relative humidity changing, along with variation in temperature. In the case of the present study, the temperature is held at 23.61°C (optimum comfortable value), and only relative humidity is changed in the analysis. It indicates that when the temperature is at the maximum comfortable position, the effect of relative humidity is inversely proportional.

#### 4.3.6 Effect of Temperature and VOC on Thermal Comfort and its impact on Occupant Productivity

This relationship presents the effect of temperature and VOC on thermal comfort and its impact on occupant productivity. The plots highlight that temperature has a very positive effect on occupants when it ranges from 22-24.5 °C and a positive effect when it ranges from 21 - 25°C. While the VOC effect is influenced by temperature, plots indicate that it has a positive impact when VOC free air is above 65%. The optimum performance is observed at 22-24°C and above 90% (VOC free air).

#### 4.3.7 Effect of Temperature and Carbon Dioxide on Thermal Comfort and its impact Occupant Productivity

This relationship shows the effect of temperature and carbon dioxide on thermal comfort and its impact on occupant productivity. It is outlined that optimum productivity and thermal comfort is achieved when temperature ranges between 22-25°C and $CO_2$ concentration below 650 ppm.

#### 4.3.8 Effect of Outside Temperature and Temperature on Thermal Comfort and its impact on Occupant Productivity

This relationship presents the effect of outside and inside temperature on thermal comfort and its impact on occupant productivity. The plots show that the highest level of thermal comfort and productivity is achievable when the temperature ranges between 21-24°C (indoor) and 30-40°C (outdoor).

# 5 Discussion

Response Surface Methodology outlined 17 relationships. However, nine relationships related to sound, office layout and illuminance were not considered as they have shown collinearity and high p -value. Analysis of eight graphs led to highlight the inter-relationship of various IEQ factors and their effect on thermal comfort and productivity. This analysis is presented via each IEQ factors according to their impact on thermal comfort and productivity.

## 5.1 Temperature

The temperature has highest effect on occupant’s thermal comfort and productivity. Experiment results outlined three relationships that presented the effect of temperature and V.O.C (6), Carbon Dioxide (7), and Outside Temperature (8), respectively on thermal comfort and productivity. Each relationship presented effect of each IEQ along with temperature on thermal comfort and productivity. All the IEQ factors have less effect as compared to temperature.

**Temperature > VOC**
**Carbon Dioxide**
**Outside Temperature**

## 5.2 <u>Relative Humidity</u>

The relative humidity is ranked second in terms of its effect on occupants' thermal comfort and productivity. The results outlined two relationships that presented the effect of relative humidity and Carbon Dioxide (4), Outside Relative Humidity (5), respectively, on thermal comfort and productivity. Each relationship presented the effect of each IEQ along with temperature on thermal comfort and productivity. All the IEQ factors have less effect as compared to Relative Humidity.

**Relative Humidity > Carbon Dioxide**
**Outside Temperature**

## 5.3 <u>Outside Temperature</u>

Outside Temperature is ranked third in terms of its effect on occupants' thermal comfort and their productivity. The results outlined two relationships that presented the effect of outside temperature and Carbon Dioxide (3) and Temperature (8), respectively on thermal comfort and productivity. Results show that apart from temperature, all other IEQ factors have comparatively less effect on thermal comfort and productivity.

**Temperature > Outside Temperature > Carbon Dioxide**

## 5.4 <u>Carbon Dioxide</u>

Carbon Dioxide is ranked fifth in terms of its effect on occupants' thermal comfort and productivity. The results produced four relationships that presented the effect Carbon Dioxide and Outside Relative Humidity (2), Outside Temperature (3), Relative Humidity (4), and Temperature (7) respectively, on occupants' thermal comfort and their productivity. Results show that Carbon Dioxide has a higher effect on thermal comfort and productivity than Outside Relative Humidity, but has less effect than Outside Temperature, Relative Humidity and Temperature.

**Outside Temperature**

**Relative Humidity > Carbon Dioxide > Outside Relative Humidity**
**Temperature**

## 5.5 Volatile Organic Compound (V.O.C)

VOC is ranked sixth in terms of its effect on occupants' thermal comfort and productivity. Results presented two relationships that presented the effect of VOC and Outside Relative Humidity (2), Temperature (13) on thermal comfort and their productivity. Results show that VOC has higher effect on thermal comfort and productivity than Outside Relative Humidity but less affect than Temperature.

**Temperature > VOC > Outside Relative Humidity**

## 5.6 Outside Relative Humidity

Outside Relative Humidity is ranked seventh in terms of its effect on occupants' thermal comfort and productivity. The results produced three relationships that presented the effect of Outside Relative Humidity and Volatile Organic Compound (1), Carbon Dioxide (2), Relative Humidity (5) on thermal comfort and their productivity. Results indicate all the IEQ factors have a higher effect than Outside Relative Humidity.

**Temperature**
**VOC**
**Outside Temperature > Outside Relative Humidity**
**Relative Humidity**
**Carbon Dioxide**

Above analysis outlines the effect of different indoor environmental quality factors, their parameters on thermal comfort and productivity. It also helped to rank these parameters on the basis of their effect on thermal comfort and productivity and inter-dependency between them. It also helped to propose design interventions based on the experiment. The experiment suggested that high difference in relative humidity, temperature between indoor and outdoor environment creates thermal shock and discomfort for occupants. It takes longer time for occupants to reach their thermal comfort and achieve productivity. Thus, it is recommended to create buffer zones to reduce temperature and humidity shock. Buffer zones can be created by developing shaded zones with water bodies around building entrances to create low temperature and high humidity areas. These design strategies would help to reduce the thermal shock for occupants while entering the building and enable them to achieve thermal comfort and productivity sooner when they start working inside the building.

# 6 Conclusion

This research study outlined the effect of thermal comfort on occupant productivity in office buildings. The study used response surface methodology to present regression analysis and equation that represents the relationship between occupants' comfort, productivity and indoor eight environmental quality parameters. There were 17 relationships presented along with effect of indoor environmental quality factors, their recommend range and inferences. The outlined relationships presented new dependencies of occupant thermal comfort and productivity on various indoor environmental factors. New dependences include the effect of carbon dioxide and VOC. These relationships were analysed to rank six indoor environmental parameters as per the degree of effect on occupant thermal comfort and productivity. This study has reiterated literature findings such as temperature and relative humidity have high influence on thermal comfort and productivity. However, it has also presented new inter-relationships and dependencies (Ismail et al., 2008, Humphreys, 2005). These findings would help the design professionals to design better office design that would improve occupants' comfort and their productivity. It is recommended that design guidelines for office buildings should consider occupant productivity and incorporate recommended range for indoor environmental quality parameters in respective categories and criteria. This research was conducted in Doha, Qatar and results are applicable to regions with similar climatic conditions. The research results have different implications for professionals working in design, construction and operation of office buildings. Design professionals should design office buildings that perform and attain the specified ranges of indoor environmental parameters presented in the results. Construction professionals are recommended to ensure that buildings are built as per the required specifications in the design. Building operation professionals should ensure that recommended ranges of indoor environmental quality parameters are met during the operation of the building. One criticism towards maintaining the demanding levels of indoor environmental quality parameters is that it might require higher energy. However, the profit gained from more productive and healthier occupants in the workplace would be multiple times higher than increase energy cost of the building operation. It is recommended to conduct similar research in other types of buildings such as educational, hospital and retail buildings to investigate and present tangible relationships of indoor environment's effect on occupants.

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